

# STRATEGY FOR MITIGATING COLLISIONS BETWEEN LANDSAT-5 AND THE AFTERNOON CONSTELLATION

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The NASA Goddard Space Flight Center Earth Science Mission Operations project, the French space agency Centre National d'Études Spatiales, the Argentinian space agency Comisión Nacional de Actividades Espaciales, and the United States Geological Survey all operate spacecraft in sun-synchronous frozen orbits. The orbits are planned to not place any of the spacecraft at risk of colliding with another. However, evolution of these orbits over time has compromised the safe interaction between Landsat-5 and the Afternoon Constellation. This paper analyzes the interactions between the Landsat-5 spacecraft and the Afternoon Constellation members over a period of 6 years, describing the current risk and plan to mitigate collisions in the future.

## INTRODUCTION

The NASA Goddard Space Flight Center (GSFC) Earth Science Mission Operations (ESMO) project, in cooperation with the French space agency Centre National d'Études Spatiales (CNES), the Argentinian space agency Comisión Nacional de Actividades Espaciales (CONAE), and the United States Geological Survey (USGS), operates several Earth observing spacecraft in two similar orbit planes known as the Afternoon and Morning Constellations. Spacecraft orbiting within these constellations maintain sun-synchronous frozen orbits with repeating ground tracks at a mean equatorial altitude of 705 kilometers. The discriminator between the Afternoon and Morning Constellations is the mean local time of the ascending or descending node associated with each. The Afternoon Constellation maintains a mean local time of the ascending node of 13:30 to 13:45, whereas the majority of spacecraft in the Morning Constellation maintain mean local times of the descending node in the range of 10:00 to 10:30.<sup>2</sup>

The different mean local times of the Afternoon and Morning Constellations can be considered as two identical orbit planes with different right ascensions of their ascending nodes. As a result, the two planes intersect at the high latitudes, in the vicinity of the North and South poles. The positions of both current and planned spacecraft within the Afternoon Constellation must allow for safe phasing between both constellations, despite the intersections. This assumes that all spacecraft will operate within a predetermined set of orbit requirements.

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Spacecraft within the Afternoon and Morning Constellations perform maneuvers to maintain their desired orbits and relative phasing. As with all sun-synchronous orbits, inclination perturbations cause changes in the orbit node rate resulting in changes in the mean local time at the node. Inclination maneuvers are performed to maintain each spacecraft's mean local time. However, as the inclination maneuvers are performed, small corresponding changes in the spacecraft altitude are required to maintain the ground track. Ground-track maneuvers, typically referred to as drag make-up maneuvers, will maintain the spacecraft at a higher or lower altitude. The resulting small changes in the orbital period will cause the spacecraft's position to drift along its ground-track. Given a large enough change to a mission's mean local time, the spacecraft could potentially drift close to the intersection between the constellations if it maintains its ground-track.

It's not uncommon for the requirements of a spacecraft within the Afternoon or Morning Constellations to change throughout its on-orbit lifetime. A requirements change for the Landsat 5 spacecraft and a large change to the mean local time of the Afternoon Constellation eventually led to repeated close-proximity fly-bys at their common orbit intersection. As these events became better understood, it was discovered that the first Landsat-5 fly-by of an Afternoon Constellation spacecraft began as early as late 2004. Eventually these impacted several spacecraft within the Afternoon Constellation.

This paper will introduce the current Afternoon and Morning Constellations as well as the Landsat-5 mission. It will continue to describe the close proximity fly-bys described above and detail the coordinated operations between Landsat-5 and the affected Afternoon Constellation mission during each fly-by. The effects of long-term maneuver plans will also be discussed, with the final section considering future risks associated with similar intersecting orbit planes for new or evolving missions.

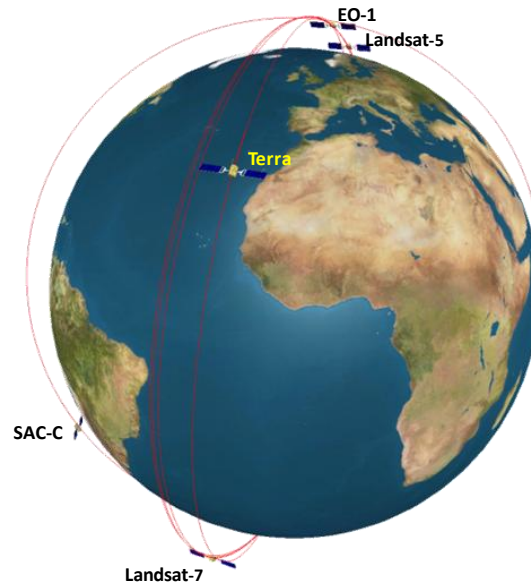
## **THE MORNING CONSTELLATION**

The Morning Constellation consists of four spacecraft: Landsat-7 (USGS), EO-1 (NASA), SAC-C (NASA/CONAE), and Terra (NASA). Only two of these spacecraft, Landsat-7 and Terra, maintain repeat ground-track orbits at 705 km mean equatorial altitude. The SAC-C and EO-1 spacecraft each maintain orbits slightly above and below 705 km, resulting in constantly changing phasing with Landsat-7 and Terra which evolves with their synodic period. The Landsat-5 spacecraft, although not considered a member of the Morning Constellation, also maintains its orbit at the 705 km altitude with a similar mean local time of the descending node (MLTDN) as Landsat-7. SAC-C maintains its MLTDN near 6:00, compared to the mean local times of 10:00 to 10:30 for the other Morning Constellation members.

The Landsat-7 spacecraft was launched in April, 1999, followed shortly by Terra in December, 1999. The orbits of both of these spacecraft were designed such that they would follow the same path along the World Reference System-2 (WRS-2) grid. Additionally, the phasing between the two spacecraft was to be maintained within 15 to 40 minutes of each other. To accomplish this, the mean local time of the descending node for Terra was established to be 25 minutes later than Landsat-7, such that Terra will cross the equator at the same longitude as traversed by Landsat-7.<sup>1</sup> Following the same WRS-2 path, this results in a 25 minute along-track separation between the spacecraft. The period of the Landsat-7 and Terra orbits allows each spacecraft to revisit a specific grid point along the equator every 16 days.

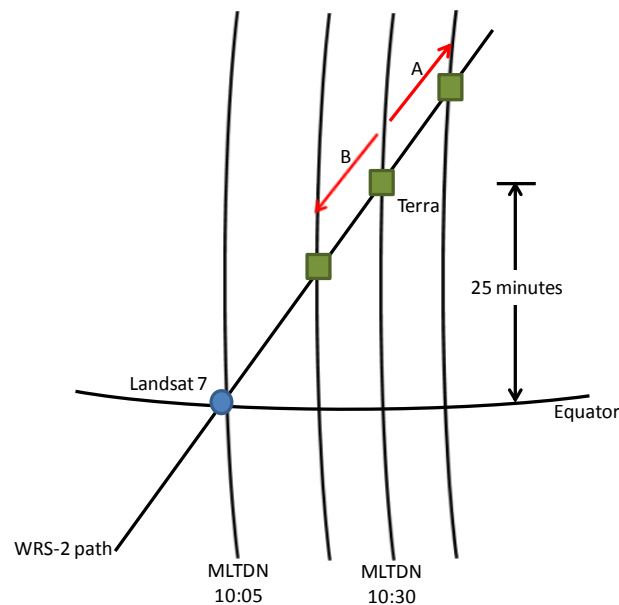
Due to perturbations such as the J2 effect, the Sun, Moon, and solid Earth tides, the line of nodes of the Morning Constellation orbits will precess, forcing the mean local times of each

spacecraft to decrease. Consequently all Morning Constellation spacecraft require inclination maneuvers to reverse the precession and maintain their mean local time requirements. Considering that Landsat-7, Landsat-5, and Terra are following WRS-2 grid points, any change to the mean local time of any spacecraft will have a direct effect on the along-track separation between them. Figure 1 represents the configuration of the Morning Constellation with the Landsat-5 spacecraft.



**Figure 1. The Morning Constellation with Landsat-5. All spacecraft are descending.**

Figure 2 illustrates the effect of mean local time drift, inclination maneuvers, and maintaining ground-track on the relative phasing of Landsat-7 and Terra.



**Figure 2. The effects of mean local time on Morning Constellation phasing.**

The curved vertical lines represent the various orbit planes, and the diagonal line indicates an arbitrary WRS-2 path. The green squares show relative positions of Terra for three different mean local times. Perturbations to the orbit planes of the Morning Constellation cause the line of nodes to precess such that the mean local time will decrease, as illustrated by arrow “B” in Figure 2. Considering that Terra will maintain the same ground-track as Landsat-7, the semi-major axis (SMA) of the orbit would decrease. This would consequently decrease the orbital period of Terra and decrease the relative phasing of that spacecraft with Landsat-7. Inclination maneuvers are planned to reverse this precession and recover the orbit to a larger mean local time, shown as arrow “A”. Arrow “A” indicates inclination maneuvers to reverse the precession and recover the orbit to a larger mean local time. In order to maintain its ground-track along the same WRS-2 path as Landsat-7, the SMA of the orbit would increase, effectively increasing Terra’s orbital period. This also increases the relative phasing of the Terra spacecraft with Landsat-7. In both cases, the nominal 25 minutes of along-track separation between the spacecraft would be impacted. Although Landsat-5 follows a different ground-track than Landsat-7 or Terra, this same relationship between mean local time and ground-track exists with that mission’s orbit plane.

The Morning Constellation members Landsat-7 and Terra are required to perform drag make-up (DMU) maneuvers in order to maintain their SMA. The SMA is reduced slightly over time due to drag forces against the spacecraft body as it orbits in the upper atmosphere. Proper maintenance of the SMA of the Landsat-7 and Terra orbits is critical in that relatively small decreases result in a drift away from the WRS-2 paths. Typical Morning Constellation DMU maneuver delta-Vs are measured in centimeters-per-second. This results in a delta-SMA in the range of tens to hundreds of meters depending on the allowable east or west excursion from the WRS-2 grid points. The location of the maneuver is often selected to best maintain frozen orbit requirements. The frozen orbit condition is generally measured against the spacecraft’s mean argument of perigee and mean eccentricity. For the Terra spacecraft, the frozen orbit requirements for mean argument of perigee and eccentricity are  $90 \pm 20$  degrees and  $0.0012 \pm 0.0004$ , respectively.

## THE AFTERNOON CONSTELLATION

The Afternoon Constellation consists of five spacecraft: Aqua (NASA), CloudSat (NASA), CALIPSO (NASA/CNES), Aura (NASA), and PARASOL (CNES). Aqua, launched in 2002, was the first spacecraft within the Afternoon Constellation, and reached its operational orbit after the Morning Constellation was formed. The exact position of Aqua was determined such that polar ground stations supporting the Terra spacecraft within the Morning Constellation would have adequate time to prepare for a subsequent pass with Aqua. This required 15 minutes of along-track separation between the times when Terra was located at the intersection of the orbit planes followed by Aqua reaching a similar point in its orbit.<sup>2</sup> The constellation assumed its current configuration when the Aura spacecraft achieved orbit in 2004, followed by PARASOL later in 2004, and lastly with CALIPSO and CloudSat in 2006. The difference in equator crossing times between the leading mission in the Afternoon Constellation, Aqua, and the trailing mission, Aura, is approximately 7 minutes and 10 seconds. This results in the configuration illustrated in Figure 3.

With the exception of PARASOL, each mission flies a near-circular orbit with a 705 km mean equatorial altitude (PARASOL was directed by CNES to lower its orbit in 2010, and hence appears out-of-phase in Figure 3 due to its different orbital period). At this altitude, the Aqua and Aura spacecraft follow the WRS-2 grid with the same 16 day repeat ground-track cycle as Terra and the Landsat-7 spacecraft. The CALIPSO mission flies a similar repeat-ground track however

its equatorial grid points are located offset 215 km east of the WRS-2 grid points. CloudSat flies in formation approximately 12.5 seconds ahead CALIPSO.



**Figure 3. The Afternoon Constellation. All spacecraft are ascending.**

The ground-track targets map directly into control box sizes that are used to maintain a relative phasing within the Afternoon Constellation, as listed below in Table 1. The Aqua and Aura ground-track requirements are twice the size of their ground-track targets.

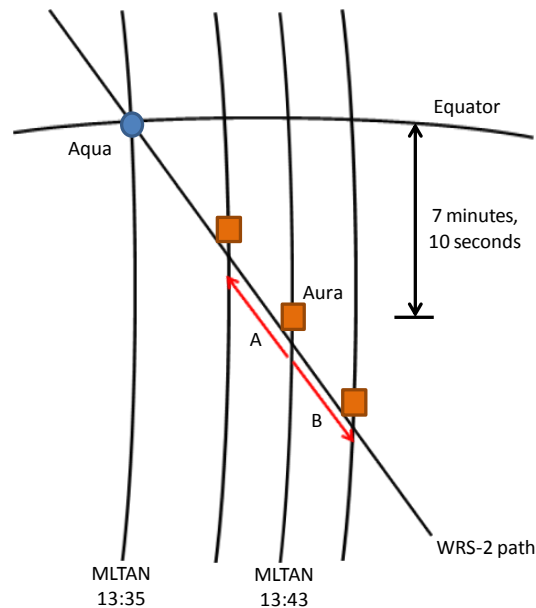
**Table 1. Afternoon Constellation ground-track targets and control box sizes.**

Spacecraft	Ground-Track Target	Control Box Size
Aqua	+/- 10 km, WRS-2	+/- 21.56 seconds
CloudSat	In-formation with CALIPSO	+15 to +20 seconds relative to CALIPSO's current location
CALIPSO	+/- 10 km, offset 215 km east of Aqua	+/- 21.56 seconds
PARASOL	N/A	N/A
Aura	+/- 10 km, offset 8km East of Aqua	+/- 21.56 seconds

Similar to the Morning Constellation, regular DMU maneuvers are performed to maintain the ground-tracks of each spacecraft within their requirements. These maneuvers also represent single burn sequences to maintain the frozen orbit requirements of each Afternoon Constellation spacecraft. The frozen orbit requirements for the Aqua and Aura missions are identical to those for the Terra spacecraft: an argument of perigee and eccentricity are  $90 \pm 20$  degrees and  $0.0012 \pm 0.0004$ , respectively.

Each spacecraft within the Afternoon Constellation must also perform inclination maneuvers to maintain the mean local time of the ascending node (MLTAN). This should not be confused

with the Morning Constellation, which implements inclination maneuvers to maintain a MLTDN. Unlike the Morning Constellation spacecraft, perturbations to the orbit planes of the Afternoon Constellation cause the line of nodes to precess such that the mean local time will increase, as illustrated by arrow “B” in Figure 4. Inclination maneuvers are planned to reverse this precession and recover the orbit to a lower mean local time, shown as arrow “A”.



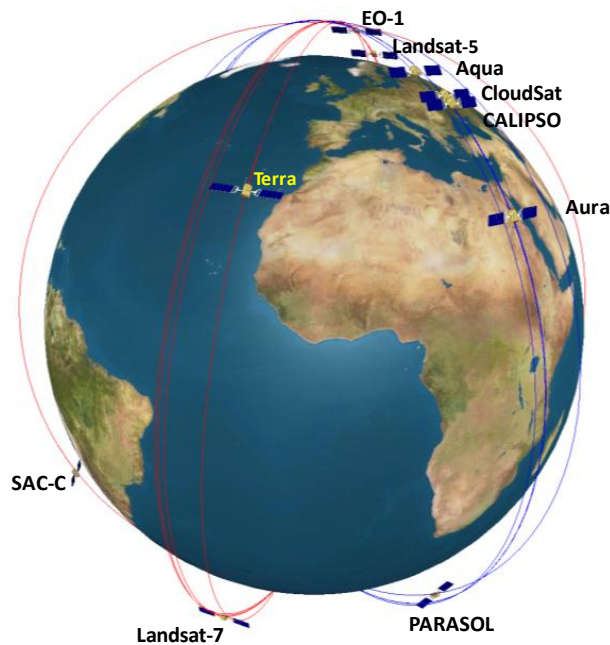
**Figure 4. The effects of mean local time on Afternoon Constellation phasing.**

Figure 4 illustrates the effect of inclination maneuvers on the Afternoon Constellation, specifically between the Aqua and Aura spacecraft. In order for Aura to maintain its position offset from Aqua WRS-2 path as inclination maneuvers are performed, the SMA of the orbit must decrease slightly to alter the orbital period. The opposite is true during a large mean local time drift relative to Aqua. Both drifting and active maneuvering will alter the relative phasing between Aqua and Aura.

## PHASING BETWEEN THE CONSTELLATIONS

The phasing of the Afternoon Constellation relative to the Morning Constellation was established to avoid conflicts with polar ground stations supporting spacecraft in either constellation. As a result, it also provides a large amount of in-track and cross-track separation between spacecraft at the intersections of each constellation’s orbit plane. Due to the similarity of the orbit planes, with the exception being the MLTAN and MLTDN, these intersections occur at the high latitude regions near the poles.

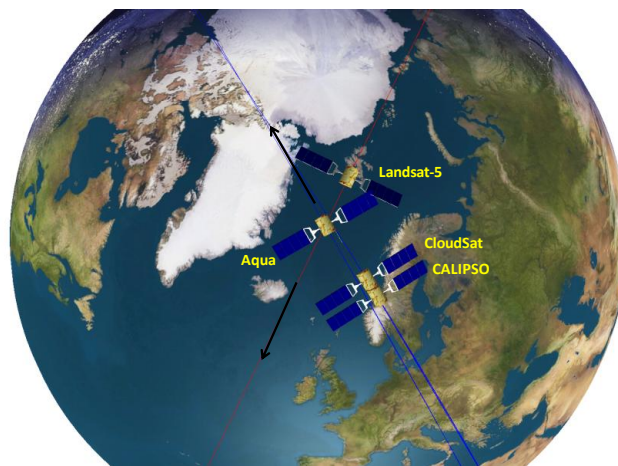
The combined orbit planes of the Morning and Afternoon Constellation spacecraft are displayed in Figure 5. At the top of the image, the 10:30 MLTDN and 13:30 MLTAN orbit planes cross near the North Pole. A similar intersection occurs near the South Pole; however that intersection is occulted by the Earth in the above image. It should be noted that the SAC-C, PARASOL, and EO-1 spacecraft do not maintain their orbits at a 705 km mean equatorial altitude, and their locations in Figure 5 are only accurate for that specific epoch. Additionally, the Landsat-5 spacecraft was typically not included in diagrams or analyses similar to Figure 5 because it was not considered a member mission within the Morning Constellation.



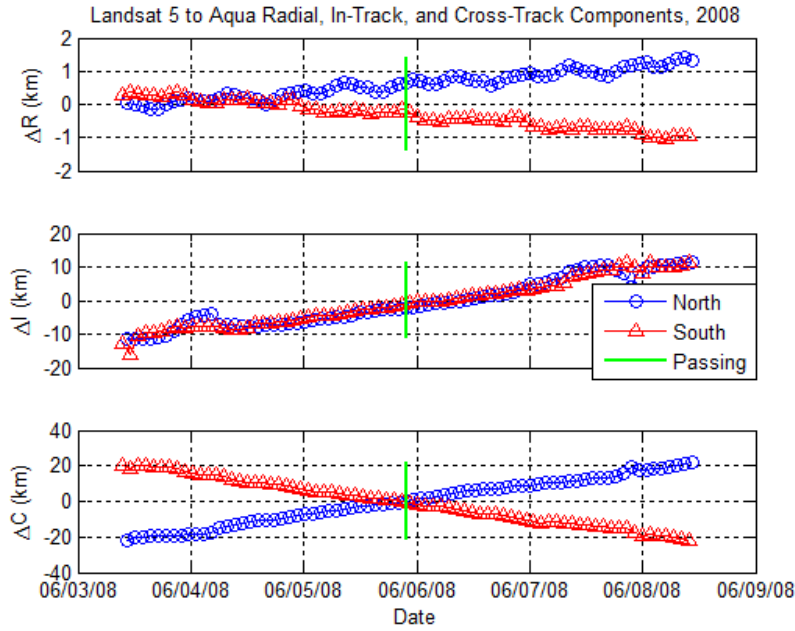
**Figure 5. The combined Morning and Afternoon Constellation orbit planes.**

## **IDENTIFYING AND CHARACTERIZING FLY-BY EVENTS**

During late February 2010, the ESMO Flight Dynamics (FD) team identified that the Landsat-5 spacecraft was undergoing several close proximity fly-bys of the Aqua spacecraft. Predictions of the Landsat-5 spacecraft further revealed that it was drifting back towards the CloudSat and CALIPSO spacecraft. During each fly-by event the in-track and cross-track separation between Landsat-5 and Aqua was observed to be nearly zero, with the radial separation oscillating between  $\pm 2$  kilometers. Furthermore, these fly-bys continued for a period of several days, repeating at a frequency of twice an orbit near the high-latitude orbit plane intersections. After analyzing definitive trajectories received from the Landsat-5 project, it was discovered that similar close proximity fly-bys of Landsat-5 have occurred with several spacecraft within the Afternoon Constellation since late 2004. Figure 6 shows an example fly-by at the northern orbit intersection.



**Figure 6. Example of a Landsat-5 fly-by of Afternoon Constellation spacecraft.**

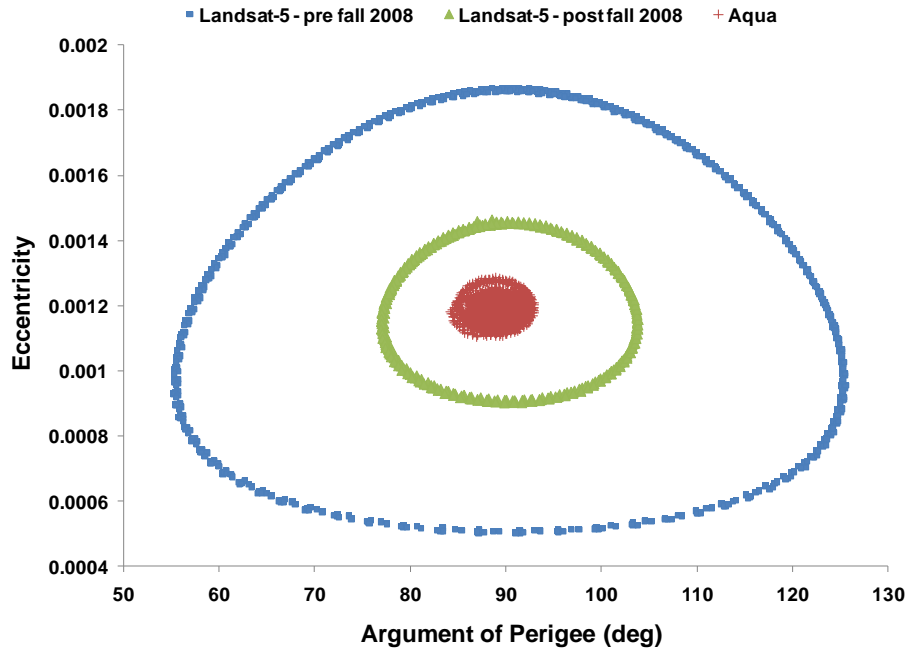


**Figure 7. Definitive components of a 2008 Landsat-5 fly-by event with Aqua.**

Definitive components of a 2008 fly-by of Landsat-5 with Aqua are displayed in Figure 7. Here, fly-by events occurring near the North Pole (blue circles) and South Pole (red triangles) orbit plane intersections are represented. The vertical line indicates the time of closest approach (TCA) in each of the three sub-plots. During this event, the in-track and cross-track components were nearly zero at the TCA, with 250 meters of radial separation at the South Pole orbit intersection and 750 meters of radial separation at the North Pole orbit intersection. Although this specific event provided serendipitous radial separation, the potential for near-zero in-track, cross-track, and radial components at each fly-by indicated that the threat of a collision between Landsat-5 and Aqua was real.

The orbit plane of Landsat-5 is advertised to be similar to those within the Morning Constellation: a sun-synchronous orbit with repeating-ground tracks. However, the Landsat-5 spacecraft does not maintain the same frozen orbit requirements as the Afternoon or Morning Constellation missions. Figure 8 illustrates the history of the Landsat-5 and Aqua frozen orbit parameters since late 2006. The outermost loop represents the frozen orbit of Landsat-5 prior to fall 2008 with the next inner loop representing the spacecraft's frozen orbit since the fall of 2008. The innermost set of points represents Aqua's argument of perigee and eccentricity from 2006 to the present. From the figure, it can be observed that the Landsat-5 frozen orbit had a much larger libration than that of Aqua. This libration indicates a continual change to the direction and magnitude of the Landsat-5 eccentricity vector. As a result this constantly altered the position and altitude of the orbit's perigee and apogee near the North and South Poles, essentially tilting the orbit plane relative to other Morning and Afternoon Constellation orbits. The behavior of the eccentricity of the orbit also provided for an oscillating radial separation that was observed between Aqua and Landsat-5 at the intersection of their orbit planes.





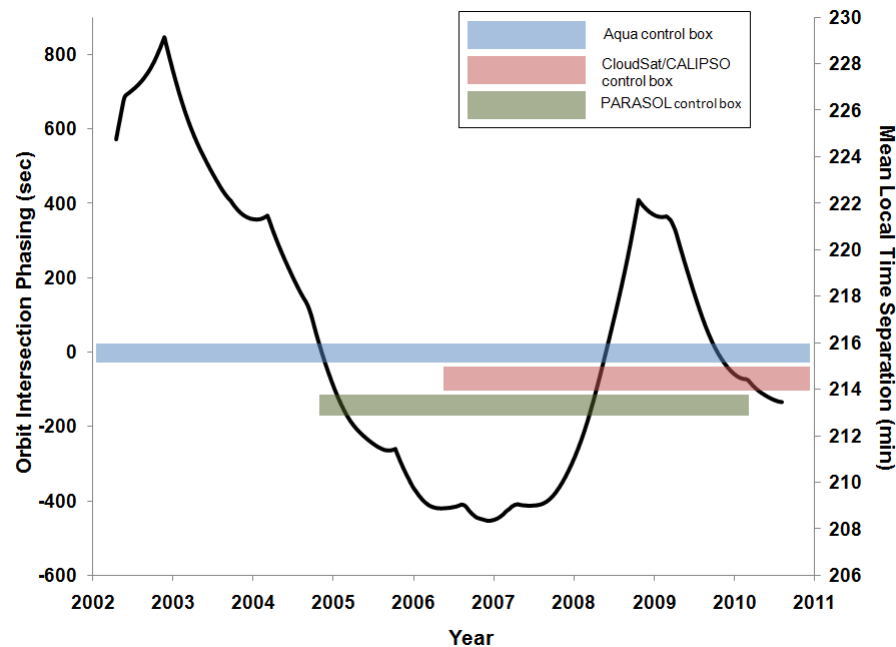
**Figure 8. Landsat-5 frozen orbit history compared with Aqua.**

The sudden change in the frozen orbit of Landsat-5 during the fall of 2008 seemed indicative that the mission had targeted a specific reduction to the libration of the orbit's eccentricity and argument of perigee. During meetings with the Landsat-5 project, it was revealed that Landsat-5 had performed a large inclination change to maintain its MLTDN. The goal of these maneuvers was to maintain the MLTDN of the orbit plane above 9:30 through 2013. This would provide for coordinated science to occur with the Landsat Data Continuity Mission (LDCM) currently scheduled to launch in 2012. It was further confirmed that these maneuvers were planned to reduce the libration from the outer loop in Figure 8 to the smaller inner loop. Unfortunately, this had the consequence of reducing the radial separation between the orbit planes from approximately  $\pm 4$  kilometers to the currently observed  $\pm 2$  kilometers.

Through further discussions with the Landsat-5 project, it was revealed that several inclination maneuvers had been performed over the course of previous years to decrease the Landsat-5 MLTDN and align its orbit plane with Landsat-7. After these maneuvers were complete, Landsat-5 would be phased with Landsat-7 by approximately 180 degrees of true anomaly. Considering that both spacecraft maintain ground-tracks that follow the WRS-2 grid, this allows the missions to reduce the 16 day repeat cycle to 8 days between both spacecraft. While this benefits the coordinated science observations occurring between each spacecraft, the large change to its MLTDN was one contributing factor to the close proximity fly-bys with spacecraft within the Afternoon Constellation. As presented in Figure 2, the large decrease in the Landsat-5 MLTDN forced the spacecraft to increase its phasing with Landsat-7 and Terra in order to continue following the same WRS-2 path. This caused the Landsat-5 spacecraft to cross the intersection of the orbit planes of the Afternoon and Morning Constellation at a similar time as spacecraft within the Afternoon Constellation.

While Landsat-5 performed maneuvers to maintain the orbit's MLTDN, the Afternoon Constellation was also performing inclination maneuvers to maintain the MLTDN of each spacecraft.

Figure 9 displays the phasing between Landsat-5 and several spacecraft within the Afternoon Constellation at their orbit's intersection (with Aqua as the reference orbit). The plot shows three series of fly-bys occurring since 2004. Since both Landsat-5 and the Afternoon Constellation maintain their WRS-2 ground-tracks, the phasing is highly dependent upon changes to the mean local time of either orbit plane. Any abrupt change to the slope of the orbit intersection phasing is an indication of inclination maneuvers performed by either Landsat-5 or the Afternoon Constellation. As a result, the second contributing factor to the close proximity fly-bys is inclination maneuvers performed by spacecraft within the Afternoon Constellation. The fall 2008 inclination maneuvers performed by Landsat-5 can be observed in Figure 9 followed immediately by a series of maneuvers performed by the Afternoon Constellation in early 2009. This forced each spacecraft to drift forward towards the orbit intersection, as illustrated in Figure 4, such that the phasing with Landsat-5 at the orbit intersection would begin to decrease. A value of zero seconds of orbit intersection phasing indicates that the Landsat-5 spacecraft is crossing the intersection at the center of Aqua's WRS-2 control box. A positive orbit intersection phasing signifies that Landsat-5 is crossing the intersection prior to Aqua, whereas a negative value will have Landsat-5 crossing behind Aqua and further into the Afternoon Constellation.



**Figure 9. Orbit intersection phasing between Landsat-5 and the Afternoon Constellation.**

Landsat-5 entered the control box of Aqua in late 2004 and resulted in the first close proximity fly-by. The control boxes of the CloudSat, CALIPSO, and PARASOL spacecraft are also illustrated in Figure 9, and were traversed by Landsat-5. There have been a total of nine fly-bys since late 2004, and each event presented a potential for a collision. Each of these events provided adequate radial separation between the orbits of Landsat-5 and each Afternoon Constellation spacecraft.

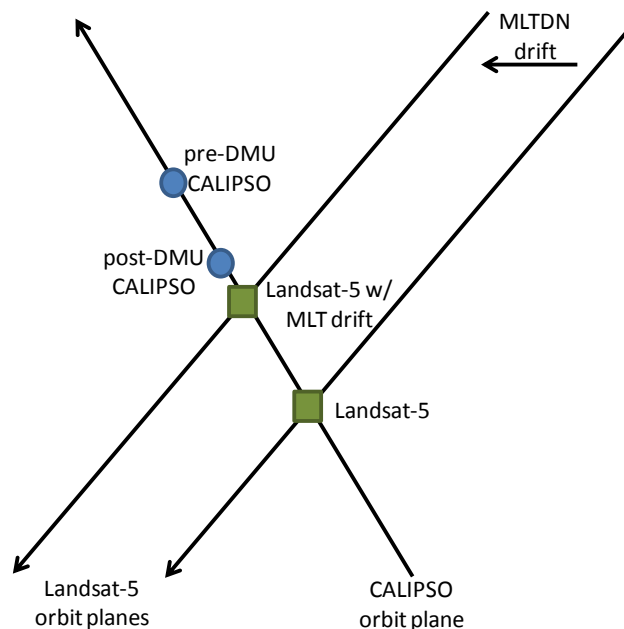
### STRATEGY FOR FUTURE FLY-BYS

Landsat-5 performed its final inclination maneuver in the fall of 2010 due to the desire to use its remaining propellant for DMU maneuvers. The Afternoon Constellation is planning to per-

form annual inclination maneuvers to maintain their mean local time range to approximately  $\pm 45$  seconds. Analysis of these mean local time maintenance plans for Landsat-5 and the Afternoon Constellation indicated that Landsat-5 would again fly-by CALIPSO, CloudSat, and finally Aqua at the intersection of their orbits beginning in September 2011. Considering that all of the involved spacecraft are still conducting nominal science operations, neither NASA nor USGS desired to decommission or de-orbit any spacecraft.

A strategy was established that would leverage the librating frozen orbit characteristics of Landsat-5 to allow Landsat-5 to safely fly-by a spacecraft within the Afternoon Constellation. Both Landsat-5 and the Afternoon Constellation would be required to analyze their DMU maneuver plans in the months preceding a fly-by event. Either spacecraft may be required to alter these plans in order to change the timing of the fly-by to occur when there is a large amount of radial separation. The target radial separation, as agreed to by both the Afternoon Constellation and Landsat-5, will be no less than 400 meters. This target will provide sufficient radial separation given limitations to orbit prediction accuracy.

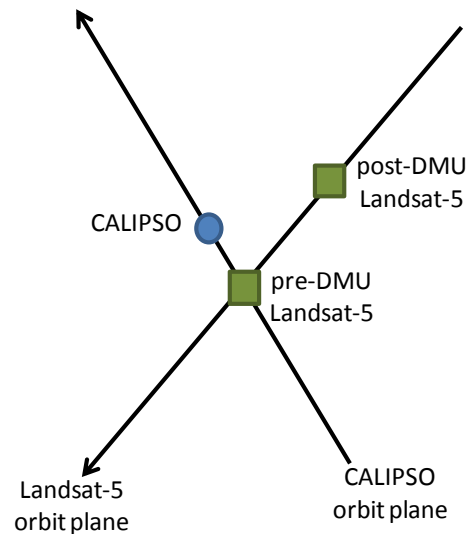
As the MLTDN of Landsat-5 decreases naturally, it will pass through the front of the Afternoon Constellation beginning with the CALIPSO spacecraft. Consequently the Landsat-5 fly-bys will approach CALIPSO from behind. As the time of the fly-bys approaches, each mission will adjust the timing or size of their planned DMU maneuvers to alter the timing of the closest fly-by. Performing these adjustments would be desirable if the predicted fly-by provided less than 400 meters of radial separation. CALIPSO or any other Afternoon Constellation member could, for instance, perform an additional DMU maneuver outside of its regular ground-track maintenance routine to force the fly-by to occur earlier. The earlier fly-by date could potentially provide a more favorable radial separation. This concept is presented in Figure 10.



**Figure 10. Effects of Afternoon Constellation DMU maneuvers on predicted fly-by date.**

In this figure, Landsat-5 is initially intersecting the CALIPSO orbit plane well after the CALIPSO spacecraft. As its MLTDN begins to decrease naturally, its intersection will begin to move towards CALIPSO, to the point where it will begin to fly-by that spacecraft. Any additional delta-

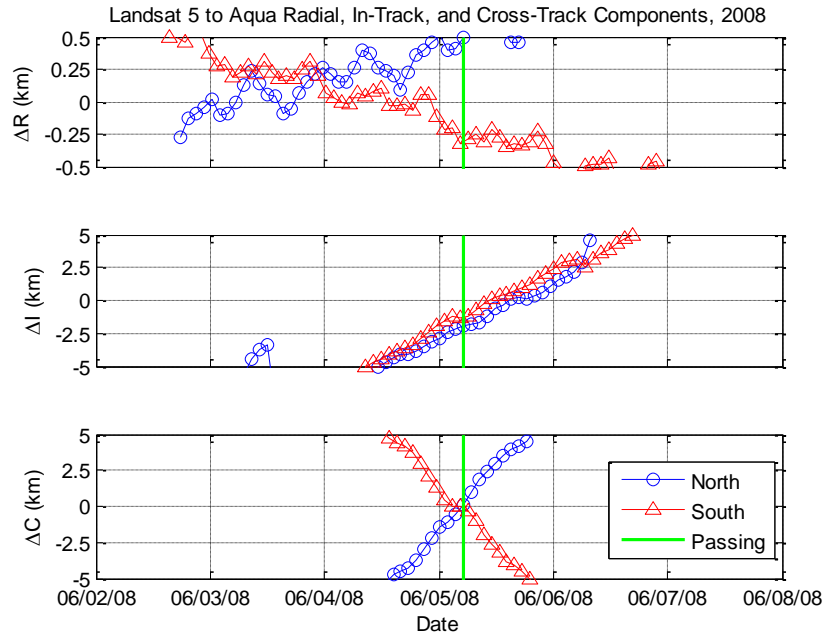
V added to the orbit through a CALIPSO DMU maneuver would provide a sudden increase to the semi-major axis of the orbit. This would increase its orbital period and effectively move CALIPSO spacecraft towards the intersection of its orbit plane with that of Landsat-5. In turn, this increase in SMA expedites the Landsat-5 fly-by of the CALIPSO spacecraft.



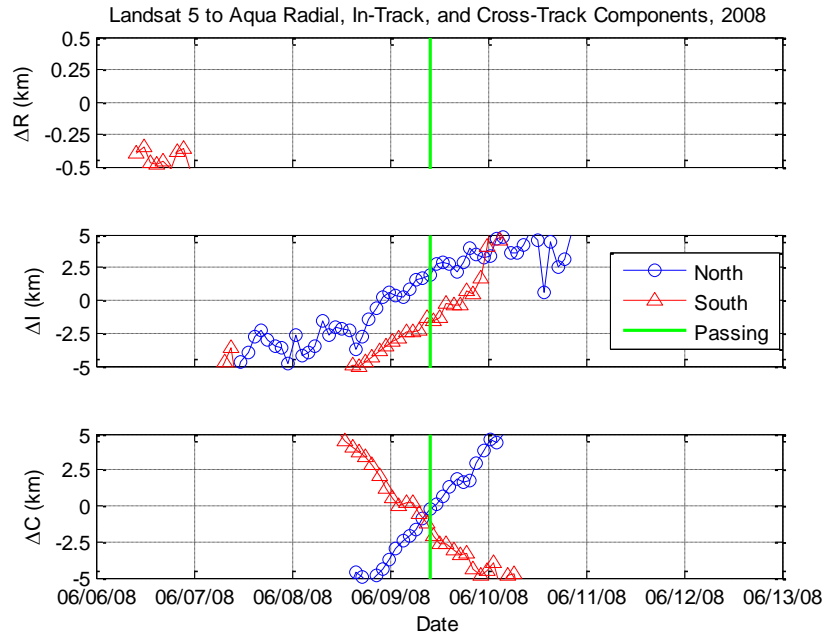
**Figure 11. Effects of Landsat-5 DMU maneuvers on predicted fly-by date.**

Contrary to the effects of Afternoon Constellation DMU maneuvers, Landsat-5 DMU maneuvers delay the date of a fly-by. Figure 11 presents both a pre- and post-DMU maneuver position of Landsat-5 relative to the CALIPSO spacecraft. Similar to the CALIPSO DMU in Figure 10, this maneuver increases the semi-major axis and period of the orbit. This effectively increases the phasing of Landsat-5 with the intersection of the CALIPSO orbit plane.

A previous fly-by of Landsat-5 with Aqua was used to prove that DMU maneuvers will provide the results illustrated in Figure 10 and Figure 11. For this case, the 2008 fly-by was selected considering that the geometry is identical to the upcoming fly-bys: Landsat-5 will approach the Afternoon Constellation from behind each spacecraft, as previously described. The definitive in-track, cross-track, and radial components of the 2008 Landsat-5 fly-by of Aqua were presented in Figure 7. A 0.5 centimeter-per-second Aqua DMU maneuver was simulated approximately ten days before the predicted fly-by. Figure 12 represents the results of the Aqua DMU maneuver, showing any radial separation within  $\pm 500$  meters. The DMU maneuver adjusted the fly-by date by approximately 16 hours in addition to moving Aqua towards a smaller radial separation with Landsat-5. However, if a 1.5 centimeter-per-second Landsat-5 DMU maneuver occurred ten days before the fly-by, this would delay the date by 3.5 days, as evident in Figure 13. Here, the new date for the Landsat-5 fly-by of Aqua provided over 500 meters of absolute radial separation at both the North and South Pole.



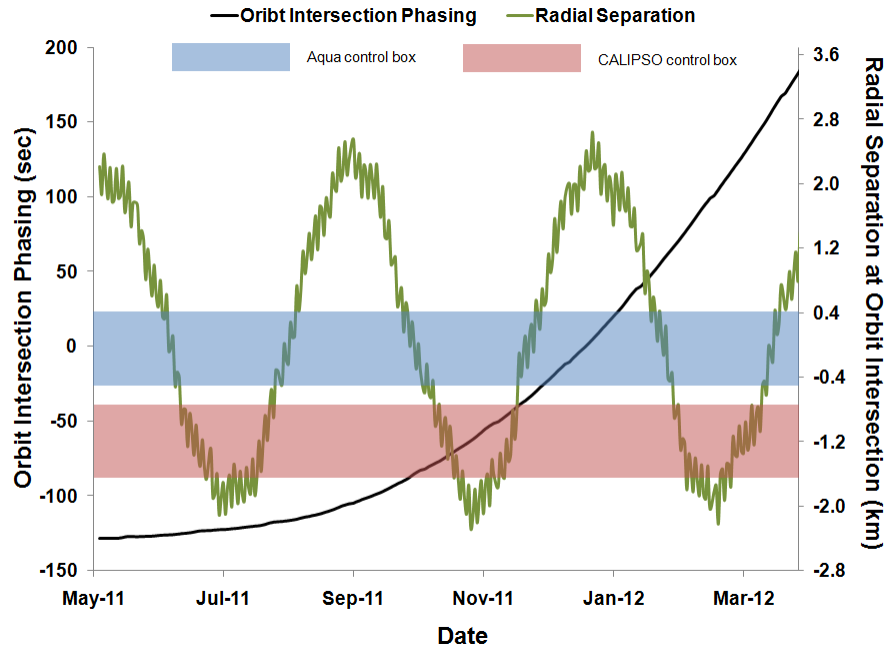
**Figure 12. The 2008 fly-by of Landsat-5 with Aqua, with Aqua DMU.**



**Figure 13. The 2008 fly-by of Landsat-5 with Aqua, with Landsat-5 DMU.**

If a predicted fly-by is revealed to occur during a period where the radial separation is below 400 meters, either Landsat-5 or an Afternoon Constellation spacecraft can adjust their regularly scheduled DMU maneuvers or perform an additional maneuver. The DMU maneuver type, whose performance is fairly well defined for any of the aforementioned spacecraft, will expedite or delay the fly-by such that it occurs with a larger radial separation.

Figure 14 illustrates the predicted Landsat-5 passage through the Afternoon Constellation. This displays the potential fly-bys with CALIPSO and Aqua, as presented in Figure 9, considering the position of Landsat-5 as it maintains its ground-track. The orbit intersection phasing is relative to Aqua's WRS-2 ground-track. Considering that the CALIPSO control box is located 30 to 73 seconds behind the Aqua control box, we can approximate the passage of Landsat-5 through their control box as shown in Figure 14.



**Figure 14. Current predicted Landsat-5 fly-bys and resulting radial separation.**

Given the current prediction, Landsat-5 will pass through the CALIPSO control box during the early-October through mid-November timeframe, as shown in Figure 14. The actual time of the fly-by is dependent upon the location of CALIPSO in its WRS-2 control box. For example, if CALIPSO was located in the center of its WRS-2 control box, the fly-by would occur in late-October. At this time, the predicted radial separation between CALIPSO and Landsat-5 is -2 kilometers. Likewise, if CALIPSO was located in the back (bottom as illustrated in Figure 14) of its control box in late-September, the radial separation between CALIPSO and Landsat-5 would be approximately -200 meters, below the desired 400 meters of absolute radial separation required for a safe fly-by. The actual date and subsequent radial separation during the fly-by will be driven by executing the previously introduced DMU maneuver strategy. This will ultimately provide for an appropriate amount of radial separation between each spacecraft to mitigate any collision risk.

## CONCLUSIONS, RECOMMENDATIONS, AND FUTURE WORK

Although Landsat-5 has a very similar orbit plane to the Morning Constellation, it was never considered a member spacecraft. Analysis performed to maintain the safe phasing between the Afternoon and Morning Constellations, therefore, did not include Landsat-5. As the missions of Landsat-5 and the Afternoon Constellation evolved, their mean local time requirements changed. Both Landsat-5 and the constellation performed large inclination maneuvers to adjust their mean local time to respond to these new requirements, putting into effect a series of close-proximity

fly-bys occurring over several years. A strategy has been developed which takes advantage of the dynamics of these fly-bys to mitigate collisions between Landsat-5 and the Afternoon Constellation. This strategy will be executed throughout the next year, until Landsat-5 completes its next and final passage through the Afternoon Constellation.

For on-orbit spacecraft, it is recommended that the mission fully quantify the risks associated with even slight changes to their orbit plane. This can be completed by quickly analyzing the environment of their destination orbit plane for any potentially active spacecraft. Any risk posed by debris could be analyzed by a conjunction assessment process. In the case of Landsat-5 and the Afternoon Constellation, large changes to a relatively simple orbit characteristic almost led to dire consequences. Spacecraft planned to maintain sun-synchronous orbits may want to consider a mean local time control box in order to limit large mean local time variations. If a similar scenario as discussed in this paper is realized by an on-orbit spacecraft, a mission should be prepared to establish lines of communication as quickly as possible. The USGS and NASA were able to communicate quickly and effectively over a period of several months to fully understand their situation and respond with an appropriate strategy.

The ESMO FD team continues to develop an analytic tool to predict the effect of DMU maneuvers on the phasing between Landsat-5 and specific Afternoon Constellation spacecraft. At the moment, the effects of these maneuvers can only be obtained numerically through simulation. This increases the time necessary to assess the effectiveness of a given maneuver, research different approaches, and propose these alternatives to the mission.

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